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**Synopsis for Registration as Research Scholar**

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# Some Investigations on Nature Inspired Metaheuristic Algorithms for Multivariable Control Systems

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# Some Investigations on Nature Inspired Metaheuristic Algorithms for Multivariable Control Systems

**Abstract:** Most of the industrial processes have been witnessing increasing complexity as they involve the objective of maintaining several controlled variables at independent set points. Controlling such multivariable systems also known as multi-input, multi-output (MIMO) control systems is quite challenging task due to presence of interactions. Control schemes for MIMO systems can be implemented either by using decentralized or centralized PID configuration. PID control is widely used due to its simplicity and efficiency. Optimal tuning of a PID controller can be achieved by identifying the finest set of proportional, integral and derivative gains. This could be achieved by using various nature inspired metahuristic algorithms.

In this work, tuning of decentralized and centralized PID controllers using nature based metaheuristic approach is presented. Bio inspired algorithms like particle swarm optimization (PSO), bacterial foraging optimization (BFO), bat algorithm, firefly algorithm etc. can be used to find optimal set of PID gains. Some algorithms will be studied and compared based on simulation results. for implementation on a typical MIMO system. On the basis of simulation results obtained for various algorithms are analyzed to identify a comparatively better method in terms of simplicity, consistency, steady state and transient responses and computational efficiency.

**Objectives**

The main objective of the proposed work is to utilize bio inspired approaches to determine the controller tuning parameters for squared multivariable systems. To achieve this following objectives are set:

1. To calculate quantitative measures of interaction existing in MIMO system.
2. To use this interaction measure to select the pairing of controlled and manipulated variables.
3. To investigate the effectiveness and applicability of bio inspired metaheuristic for MIMO PID controller problem.

4. To formulate the tuning of multivariable controller as an optimization problem using objectives like minimizing integral absolute error (IAE), integral square error (ISE) etc. and to optimize PID gains.
5. To compare and analyze results obtained using various bio inspired algorithms viz. PSO, BFO etc. and other conventional techniques.
6. To review and analyze the strengths and weaknesses of existing metaheuristic techniques and suggest possible improvements and/or new measures for dealing with weaknesses identified.

**Introduction**

With the development of modern industry, single-variable system cannot satisfy the demands of industrial production progressively, so the occurrence and importance of multivariable control systems or MIMO control systems has been increased in industries. Based upon the number of inputs and outputs, MIMO systems are classified as shown in figure 1.

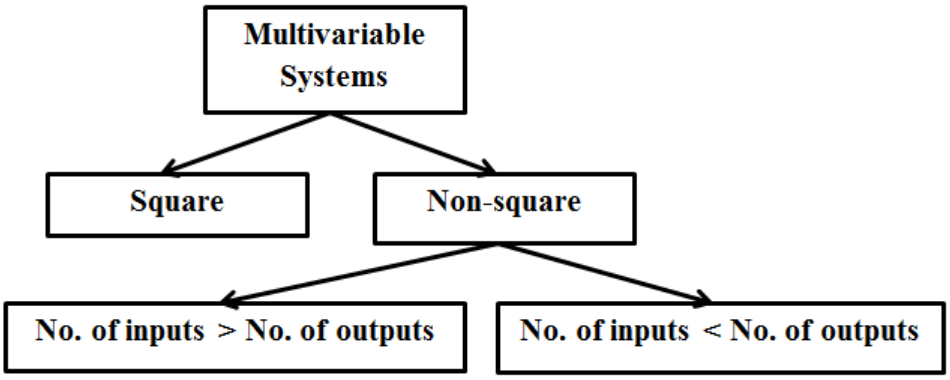


**Figure 1 Multivariable system classification**

The main characteristic that defines MIMO system is the coupling among control loops which is also called as interaction. It occurs when some outputs are influenced by several inputs and some inputs influence several outputs. Figure 2 depicts basic idea.

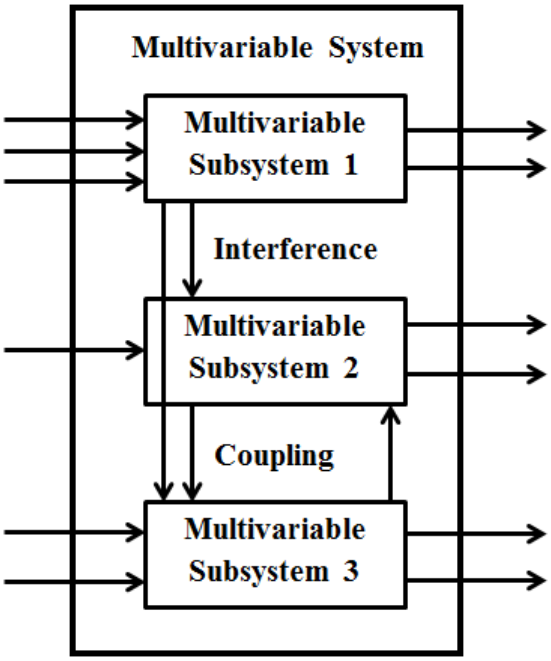


**Figure 2 Multivariable system with interaction**

There are two types of interaction:

- Interference in which some variables of subsystem influence other subsystem. But these subsystems do not influence variables of the first one. This is also called as feed forward interaction as there is no return path to the system originating the interference.
- Coupling in which there exists a path of cross influence, so that there is a hidden feedback loop.

To minimize the effect of interaction, best pairing of controlled and manipulated variables is necessary. Best pairing is achieved either by steady state gain matrix, relative gain array, Ninderlinski index, singular value decomposition, Morari resiliency index, dynamic RGA, participation matrices, Hankel interaction index array or $H_2$ norm [1].

Based on the interaction measure, to deal with the MIMO control problems either centralized PID or decentralized PID control technique is used. Decentralized control strategy is used when interactions are modest. When the interactions between the loops are strong, it is adequate to adapt centralized control scheme. But centralized controller has two deficiencies.

First, it is full matrix controller, we need to tune 3np parameters where n is the number of input and p is the number of output. Second, adjusting controller parameters of one loop affects the performance of another, sometimes to the extent of destabilizing the entire system [2].

Conceptual simple approach to design a multivariable controller is a two-step procedure in which we first design additional feed forward element called decoupler to deal with the interactions in plant and then diagonal controller called decentralized controller. One great advantage of this method is that it allows the use of single-input single-output (SISO) controller design methods. Moreover, the number of tuning parameters in this case is significantly less than that of the centralized PID.

A simple feedback system is shown in figure below [3]:

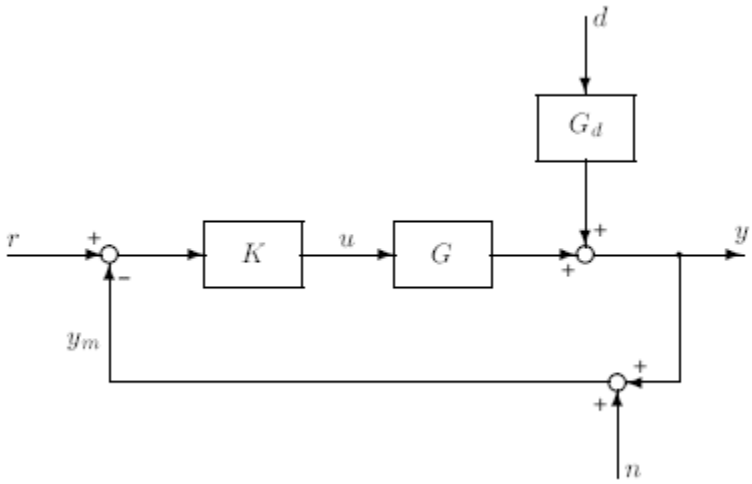


**Figure 3 Feedback control configuration**

In this approach, decoupler D(s) is designed which counteracts the interactions in the original plant G(s) to result in a new shaped plant:

$$G_s(s) = G(s).D(s) \quad (1)$$

Decoupler can be steady state or dynamic. After designing a decoupler decentralized controller $K_s(s)$ is designed for a shaped plant. The overall controller is then represented as:

$$K(s) = D(s).K_s(s) \quad (2)$$

This two-step procedure results in a sub-optimal design [skogstad]. Main challenge consists in finding optimal parameters for the decentralized controllers, so that the interaction between loops is minimized and the desired response presents a good dynamic behavior and no stationary error. The alternative is the application of optimization techniques to obtain the parameters for the controllers. Optimization in controller design becomes prominent in 1960's [3]. The systematic determination of optimal solutions leads to number of algorithms.

Optimization algorithms can be categorized as follows:

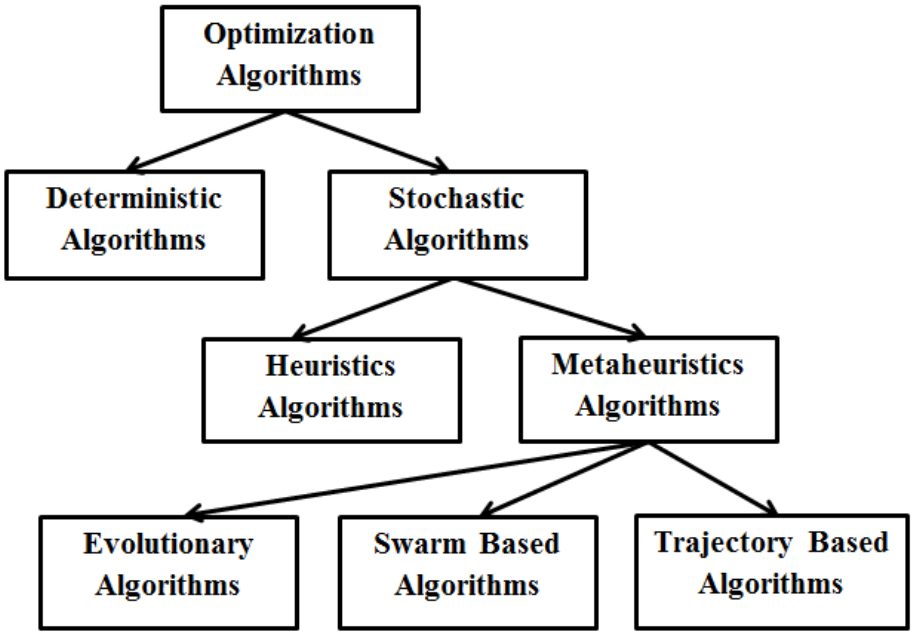


**Figure 4 Optimization algorithm classification**

Deterministic algorithms follow a precise procedure and they find the solution in same manner. They use gradient based information. Stochastic algorithms are gradient free algorithms and subdivided into heuristics and metaheuristics category. Heuristics produce an acceptable solution by trial and error. There is no guarantee to find good solutions in all the time using heuristics[4]. Thus, heuristic algorithms are further developed into metaheuristic algorithms.

Metaheuristics are high-level search procedures that apply some form of rule or set of rules based on some source of knowledge in order to explore the search space in a more efficient

way. Dr. Fred Glover proposed metaheuristic as master strategy that guides and modifies other heuristics to produce solutions beyond those that are normally generated in a quest for optimality. It cannot guarantee (in general) convergence to the global optimum, but normally provide reasonably good approximations. Because of their flexibility, generality and ease of use, metaheuristics have become increasingly popular in the last 30 years as optimizers of complex problems [4].

**Literature survey**

Multi-input, multi-output processes are more complicated in controller designing aspect as compared to single-input, single-output systems[4]. When we change one manipulated variable, then it should affect only the controlled variable associated with it. But in practice, change in manipulated variable affects other controlled variables. [6] This issue is nothing but the interaction. Interaction analysis techniques and recommendation for pairing controlled and manipulated variable were given in [7-8]. To tackle with the interaction between the control loops, decoupling control scheme is used. In [9] decoupler design from block diagram and basic principles is discussed. Decoupler for non square processes is discussed in [10]. Though at first glance, decoupling seems an appealing idea, it has some drawbacks like it may be very sensitive to modelling errors and it may not desirable for all disturbance rejection task. Decoupling elements are used to improve performance of diagonal controller. It is simple approach to multivariable control design and referred as decentralized control. However, this approach can work properly only when the interactions between the control channels are relatively moderate. In case of strong interactions between the loops, centralized controller is advised.

In order to design controller for multivariable systems with multiple time delays, different approaches like Smith predictor for MIMO case, internal model control (IMC) have been developed[11]. SISO control techniques can be applied to tune multivariable controller. Tuning rules suggested by Zeigler-Nichols (1942), Chein et al (1952), Cohen-Coon (1953), Astrom-Hagglund (1995) etc. are based on process reaction curve. Tuning rules based on direct synthesis approach were developed by Smith-Corripio (1985), Tsang et al (1993). Robust tuning methods were presented by Chien (1998), Fruehauf et al. (1993) etc. A summary of tuning rules based on process reaction curve, ultimate cycle, direct synthesis etc. applied to SISO PID controller is presented in [12].

Multivariable adaptive control methodologies such as model reference adaptive control (MRAC), adaptive decoupling control, adaptive decentralized control, self-tuning control, adaptive non-linear control etc. are surveyed in [13-14].

Standard advanced control strategy to deal with MIMO control problems is model predictive control (MPC). It provides robust and optimal solutions to the control problem. Multivariable model predictive control is briefly discussed in [15]. Although MPC technology is highly developed, a general method to tune MPC controllers is still an open research problem [16].

Recently various meta-heuristic algorithms are used to solve problems in science, engineering etc. The problem of parameter tuning of the PID controller, MPC, has been solved using a different stochastic, nature-inspired, population-based algorithms. Historical perspective of metaheuristics, detailed description of various nature based algorithms and details of algorithm implementation is presented in [17]. Detailed classification of nature inspired algorithms and comprehensive list of algorithms in literature are presented in [18-19]. Recent advances in nature-inspired computing; giving a special emphasis to control systems applications is highlighted in [20]. It reviews different techniques used for simulating physical, chemical, biological or social phenomena at the purpose of designing robust, predictive and adaptive control strategies. Cutting-edge research techniques in related computational intelligence domains and their applications in real-world process engineering are briefly discussed in [21].

A review of algorithms and scope of applications to genetic algorithms, ant colony optimization, particle swarm optimization, cuckoo search algorithm etc. are summarized in [22]. Nature-inspired optimization algorithms for optimal tuning of linear and non-linear controllers used in industrial process applications are overviewed in [23]. Classical and optimization algorithm based PID tuning techniques are compared in [24].

Evolutionary algorithms in control system engineering are surveyed in [25] and applications for controller design in addition to robustness analysis are discussed. Performance comparison of various evolutionary algorithms such as real coded genetic algorithm, differential evolution etc. on optimal design of multivariable PID controller design is done in [26].

Algorithms such as modified binary PSO, probability based binary PSO, discrete binary PSO and modified discrete binary PSO are realized in [27]. Also comparative performance analysis of these algorithms on optimal PI and PID controller design for MIMO process is stated. Development of the control methods for non-square systems, theories about the IMC – PID and multivariable IMC - PID controller design method for non-square large time delay systems based on EOTF using NPSO algorithm are discussed in [28].

Fundamentals of firefly algorithm are discussed in [29]. Also, new chaotic firefly algorithm (CFA) approach based on Tinkerbell map to tune multi-loop PID multivariable controllers is proposed.

A comprehensive and exhaustive overview of the cuckoo search algorithm (CSA) and it's applications are briefly discussed in [30].

Brief discussion on the potential uses of biomimicry of social foraging to develop adaptive controllers is featured in [31].

**Proposed hypothesis**

The research work focuses on application of bio inspired metaheuristic approach for control of multivariable systems. Earlier studies of application of bio inspired metaheuristics in process control application gives the scope of research in this domain.

For MIMO system, it is necessary to calculate quantitative measure of interaction and to use this interaction measure to select the pairing of controlled and manipulated variables that reduces the effect of interaction. It can be eliminated through the design of an appropriate control system and the simplest way is to use decoupling control strategy [6-9]. Decoupler can be simplified, ideal or inverted.

Based on the interaction analysis, controller strategy viz. centralized or decentralized PID controller is chosen. Although classical PID tuning methods are widely used, sometimes, their behavior does not correspond to the desired. Rather than using conventional techniques, multivariable control system can be designed by using nature inspired algorithms which evolve solutions using cost function and optimization. It presents viable solutions, even if it is not the best [24].

**Methodology to be used and adapted**

Multivariable control is a research area presenting both theoretical challenges and practical significance, with unique technical issues like interactions, environmental uncertainties, stability, multiple time delays etc. To achieve the above stated objectives, appropriate methodology should be chosen to cope up with these issues.

One of the measures for degree of directionality and level of interaction for squared MIMO system is the relative gain array (RGA) suggested by Bristol. Transfer function matrix for two input, two output process is given as:

$$G(s) = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \tag{3}$$

Relative gain is calculated by using steady state gains of process transfer function which is represented as:

$$SSGM = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \tag{4}$$

Relative gain is calculated by using below equation:

$$\mu_{ij} = \frac{gain\ when\ all\ other\ loops\ are\ open}{gain\ when\ allother\ loops\ are\ closed} = \frac{K_{ij}}{K'_{ij}} \tag{5}$$

Relative gain matrix is represented as:

$$RGM = \begin{bmatrix} \mu_{11} & \mu_{12} \\ \mu_{21} & \mu_{22} \end{bmatrix} = \begin{bmatrix} \mu_{11} & 1-\mu_{11} \\ 1-\mu_{11} & \mu_{11} \end{bmatrix};\ \mu_{11} = \frac{1}{1-\frac{K_{12}K_{21}}{K_{11}K_{22}}} \tag{6}$$

As per Bristol's pairing rule, to minimize the interaction between loops, always pair on RGM elements that are closest to 1.0. Avoid negative pairings.

Interaction between the loops can be suppressed by using a control scheme called as decoupling control. The relative gain matrix provides an indication of when decoupling could be

beneficial. When checking for interactions, each element in a column is divided by the relative gain of the pairing chosen in that column, taking the reciprocal if the result is less than 1. If the absolute value of the result is in between 1 and 1.25 then this indicates that the interaction is strong enough to require decoupling to avoid instability. If the value is in between 1.25 and 1.5, the interaction is significant and some form of decoupling would be beneficial. For values between 1.5 and 2, interaction is mild and decoupling would provide no noticeable improvement.

Control problems can be formulated as optimization under constraints of an appropriately selected objective function. The objective function is in general a function of the state, the output, the control input and/or the external input variables that may express several design goals such as energy consumption minimization, minimization of settling time, tracking error minimization etc. A usual approach is to control the system using a controller with specific structure, while the objective function is expressed as multivariable function that depends upon the controller parameters. Then, the optimization under constraints problem is solved to derive set of controller parameters that achieve optimal performance with respect to the cost criteria. Generalized view of metaheuristic approach is as shown in figure below:

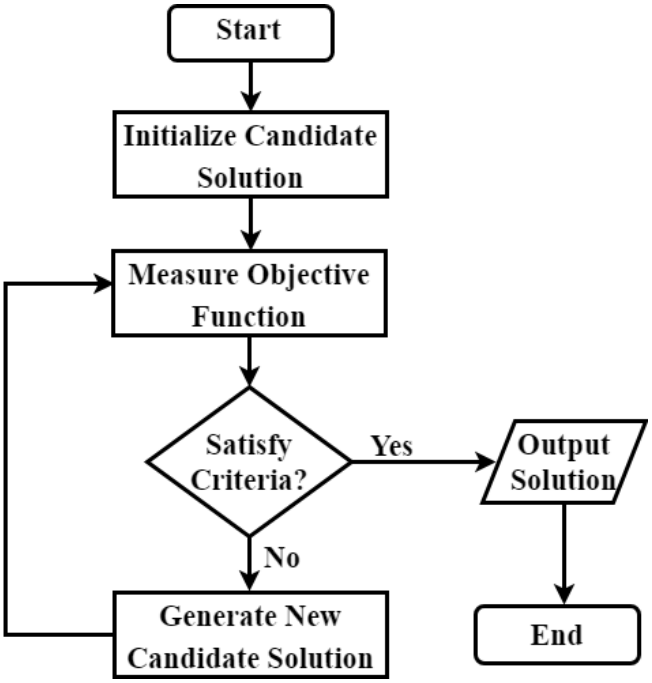


**Figure 5 Generalized view of metaheuristic approach**

Candidate solutions are initialized randomly. Some common choices for objective functions in time domain considering figure 3 are as follows:

$$IAE = \int_{t=t_0}^{\infty} |r(t) - y(t)| dt \tag{7}$$

$$ISE = \int_{t=t_0}^{\infty} (r(t) - y(t))^2 dt \tag{8}$$

$$ITAE = \int_{t=t_0}^{\infty} t|r(t) - y(t)| dt \tag{9}$$

These objective functions are minimized in search space where dimension of search space is equivalent to number of parameters of PID to be tuned.

The use of these nature based algorithms for tuning controller makes possible to get controllers gains reaching as fastest as possible responses with less overshoot, presenting errors in steady-state regime near to zero.

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